A MODEL FOR MARINE CORPS ENGINEER PLANNING

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THESIS

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ABSTRACT

Given an engineer force structure and a set of projects to be completed in a specified time period by the units of the force structure, the problem which is examined is that of efficient utilization of the excess labor in some skills which is likely to be available after completion of the minimum number of projects. A model is developed in terms of a vector maximization problem. This is reduced to a linear programming problem, which is further reduced to a problem which can be solved by algebraic means. A test problem is run and results presented. A suggestion for an additional use of the model is included.

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I. INTRODUCTION

A. PROBLEM TO BE STUDIED

The problem of determining engineer force levels required to complete a given set of tasks in a theater of operation has been discussed by Kitts [Ref. 1]. The present paper takes the force structure as given (an extension suggested by Kitts) and addresses the problem of project selection, over and above certain minimum levels, subject to the force structure. This formulation is considered to be a more useful and realistic model for application to Marine Corps engineer planning for several reasons.

Kitts assumes the availability of a wide variety of types of engineer units of various degrees of specialization. While such a wide variety may exist in the U.S. Army, it does not exist in the U.S. Marine Corps.

For missions with a fairly long lead time (on the order of months), the Marine Corps could activate new engineer units or mobilize reserve engineer units to accomplish any task which might reasonably be assigned. However, as the Nation's amphibious force-in-readiness, the Marine Corps must be prepared to deploy on short notice forces <u>in being</u>, including engineer forces, under combat conditions or conditions of crisis short of war.

There might exist non-combat or non-crisis situations in which lead times on the order of months would be available. For example, an engineer unit might be deployed to the site of a future training exercise to construct base camp facilities for the participants in the exercise. Deployments such as these would generally have durations measured in

weeks or a very few months, so that activation and/or mobilization of new engineer units for such a short period of active service would not be practical.

B. MARINE CORPS ENGINEER UNIT MISSIONS

The mission of the Engineer Battalion, Marine Division, Fleet Marine Force, is stated in Ref. 2. In general, this mission is oriented toward combat support of infantry units. In combat operations, the number and types of specific tasks this type of engineer unit will be required to perform is usually not known with any degree of certainty prior to the start of the operation. The model which will be developed in this paper is not capable of handling this uncertainty.

Units such as the Topographic Platoon, Fleet Marine Force and Bridge Company, Fleet Marine Force are small and have rather narrowly defined missions [Ref. 2]. The model developed in this paper would not be applicable to these units.

The mission of the Engineer Battalion, Fleet Marine Force [Ref.2] is oriented toward the accomplishment of assorted engineer tasks of a more deliberate nature. Generally, the numbers and types of these tasks will be known with much greater certainty than will be the case for the Engineer Battalion, Marine Division, Fleet Marine Force. This paper is primarily oriented toward the Engineer Battalion, Fleet Marine Force. However, the model could be applied to any engineer unit in any situation in which future tasks were known with certainty.

C. DEFINITIONS OF TERMS

The term "project" as used in this paper is deliberately left very loosely defined. A project can be a structure such as a messhall or

dispensary, or it can be a segment of road, a runway, etc. Or, it can be the upgrading of some existing building, road, etc. A project must have the property that man-hours of labor (and/or equipment hours) must be expended by an engineer unit to complete the project. Further, there must exist estimates of the number of man-hours or equipment hours in various categories (carpenter, electrician, dozer, crane, etc.) required to complete the project. For the sake of brevity, the term "man-hours" will be used for either man-hours or equipment hours until it is necessary to explicitly make the distinction between the two terms.

Hereafter, the term "planners" will frequently be used. This term may refer to the operations staff of an Engineer Battalion, it may refer to the staff of the commander having operational control of an Engineer Battalion, or it may refer to the staff of a commander several steps up the chain of command, preparing a contingency plan.

D. USE OF THE MODEL

The model developed in this paper could be of use in the following general situation: A U.S. Marine Corps Engineer, Fleet Marine Force is tasked with completing a specified set of projects within a specified period of time. This may be an actual situation, or a hypothetical one, such as a war game. Two specific examples of this type of situations are given below.

In an amphibious operation, "8th Engineer Battalion lands commencing on D + 2 and completes a specified set of projects by D + 30."

Or, in a non-combat situation, "9th Engineer Battalion deploys forces from Okinawa to Camp Fuji, Japan to complete a specified set of projects. Shipping is available from Okinawa to Japan only during

the period 1-5 October, and from Japan to Okinawa only during the period 11-15 November."

E. ENGINEER PLANNING

Given a specified set of projects to be completed within a specified time period at a specific geographic location (or locations) with a given engineer force, the planners must first ascertain that completion of all the projects is feasible. Completion is considered to be feasible if it is possible to schedule work on the projects so that all will be completed on time and if the number of man-hours available within the engineer force in each skill is greater than or equal to the number of man-hours of each skill required to complete all the projects. Presumably, some technique such as PERT or CPM would be used to schedule the projects. If the schedule forces some personnel to be idle for some time period, then the man-hours lost are not "available" in the sense of the above definition of feasibility. If completion of the projects is feasible, it is unlikely that the supply of labor in each skill type would exactly be exhausted. That is, it is likely that in some skills there will be excess labor available. This is because labor comes in large units which contain many skill types, i.e., battalions, companies, etc. Or, as in one of the examples in the preceding section, transportation availability, or other factors which are outside the control of the planners, may require the engineer force to remain at the site of the projects until a certain date. This excess labor should be used to complete "desired" projects, over and above minimum requirements.

It is unlikely that there will be a unique project or set of projects that can be completed with the available excess labor. Thus, the planners need a method of presenting to the decision-maker (presumably

a commander at some level) alternative sets of desired projects that make productive use of the excess labor. This paper discusses a method which could be used to examine these sets of projects and the tradeoffs between them.

It is presumed that the decision maker has specified which project types are to be considered "desired" projects. Usually, this number will be small compared to the total number of project types. This is so because, for most project types, the maximum number required is the same as the minimum number. That is, a specific number, no more, no less, is required. For example, in a 500-man camp, only one 500-man messhall is required, only one dispensary adequate for the expected patient load is required, etc. Desired project types will usually be such things as additional housing units (to provide roomier quarters for personnel), additional warehouse buildings (to provide more covered storage space for supplies), additional miles of improved road in and around a camp, etc. The model developed in this paper allows three project types to be specified as desired project types. As discussed later it is difficult to analyze tradeoffs between more than three project types.

II. MATHEMATICAL DESCRIPTION OF THE MODEL

A. THE VECTOR MAXIMIZATION PROBLEM

The model is described mathematically as follows:

$$\begin{aligned} &\text{"maximize"} \quad Y \\ &\text{subject to:} \quad AY \le B \\ &\qquad\qquad\quad\;\; Y \ge C \\ &\qquad\qquad\quad\;\; Y \ge 0 \end{aligned}$$

Y is a column vector of order n, $(y_1, \ldots, y_n)$. The element y_j represents the unknown number of units of project type j to be completed. There are n types of projects. For some project types, it may be required that y_j be an integer.

B is a column vector of order m, $(b_1, \ldots, b_m)$. The element b_i is the number of man-hours of skill type i available within the engineer force. There are m skills required to complete the projects.

A is an m x n matrix. The element a_{ij} is the number of man-hours of skill i required to complete one unit of project type j.

C is a column vector of order n, $(c_1, \ldots, c_n)$. The element c_j represents the minimum number of units of project type j which must be completed.

Physically, the model only makes sense if $c_j \ge 0$. Then, the constraint $Y \ge 0$ is unnecessary.

B. THE OBJECTIVE FUNCTION

The objective function to be maximized in this program is a vector Y with n components, $y_1, y_2, \ldots, y_n$. A vector Y^o (which satisfies all constraints) with components $y_1^o, y_2^o, \ldots, y_n^o$ is <u>not</u> a solution of

the "maximization" problem is there exists a vector Y^1 (which also satisfies all constraints) with components $y_1^1, y_2^1, \ldots, y_n^1$ such that $y_j^1 \geq y_j^o$ for all j, and for at least one value of j, say p, $y_p^1 > y_p^o$. Vectors like Y^o are called dominated. Vectors which are not dominated by any other vector are called undominated, and undominated vectors are also called efficient points. Each feasible undominated vector is a solution to the "maximization" problem.

The element y_j represents the number of units of project type j to be completed. If all units of project type j must be completely finished by the engineer unit, then y_j must be an integer. If one or more units of project type j can be partially finished by the engineer unit and completed by the using (or other) unit, then y_j need not be an integer.

C. THE TECHNOLOGY MATRIX

The constraints $AY \leq B$ can be written as:

$$\sum_{j=1}^{n} a_{ij} y_j \leq b_i, \; i = 1, \ldots, m.$$

Writing the constraints in either of these forms implies constant returns to scale, or a linear technology. For the ranges of the components of Y under consideration, a linear model is considered appropriate.

An element a_{ij} of the technology matrix represents the man-hours of labor of skill i required to complete one unit of project type j. A major problem exists in obtaining these coefficients in a directly useful form. This problem will be discussed later in this paper.

D. THE RESOURCE AVAILABILITY VECTOR

An element b_i of the resource availability vector represents the number of man-hours of skill i available within the engineer force during

the time available for completing the set of projects. The level of aggregation of the b_i's (with respect to the skill types) can be as fine or as coarse as desired. However, the level of aggregation can be no finer than the available estimates of required man-hours for the various project types. In other words, the skill represented by the subscript i in the element b_i must correspond to the skill represented by the subscript i in the coefficient a_{ij}.

In general, the numerical value of an element b_i will depend on the time available to complete the set of projects and on the number of men within the engineer force who possess skill i and who are available for direct labor on the projects. To compute B, let D be a column vector of order m, whose elements d_i represent the number of men in the engineer force with skill i and who are available for direct labor on the projects. Then, $B = hD$, where h = (number of working days available to complete the projects)·(number of working hours per day)·(production factor). The number of working hours per day will depend on the operational situation and the number of hours of daylight per day. The production factor must account for such things as personnel who are on mess duty, security duty, leave, hospitalized, in the brig, etc., for weather and climate; and for interference with work by enemy activity.

In some cases, b_i will actually be available equipment-hours rather than man-hours. In these cases (with the assumption that sufficient operators are always available), $B = hFD$, where F is an m x m diagonal matrix with elements f_i, which represent the percentage of time a unit of equipment type i is expected to be operational. Here, d_i is the number of units of equipment type i owned by the engineer force.

E. MATHEMATICAL CHARACTERIZATION OF SOLUTIONS TO THE VECTOR MAXIMIZATION PROBLEM

As described in Refs. 8 and 9, solutions to the vector maximization problem described earlier are characterized by solutions to the following mathematical program:

$$\begin{aligned} &\text{maximize} \quad \psi^T Y \\ &\text{subject to: } AY \leq B \\ &\qquad\qquad\quad Y \geq C \\ &\qquad\qquad\quad \sum_{j=1}^{n} \psi_j = 1 \quad . \end{aligned}$$

ψ is a column vector of order $n, (\psi_1, \ldots, \psi_n)$. Each element ψ_j represents a weighting factor associated with project type j.

In general there will be no unique solution to the above program. There will be a solution for each different ψ, and these solutions need not be the same. If the planners could find the solution corresponding to each possible ψ vector, the decision maker could choose the solution he most preferred. This is not practical, however, since generally there will be an uncountable or nondenumerable set of ψ vectors. Further, if more than two or three components of the Y vector are allowed to vary simultaneously, it is difficult for the decision maker to comprehend the tradeoffs between the project types. Assume that only two components of Y are allowed to vary and that there is only one skill type. Consider Figure 2.1. Here it is easy for the decision maker to visualize the tradeoffs between project types 1 and 2. Any combination of y_1 and y_2 which lies on the line EE' is an efficient point. It is also easy if three of the components of Y are allowed to vary. Consider Figure 2.2. Here, the set of efficient points is the facet EE'E''.

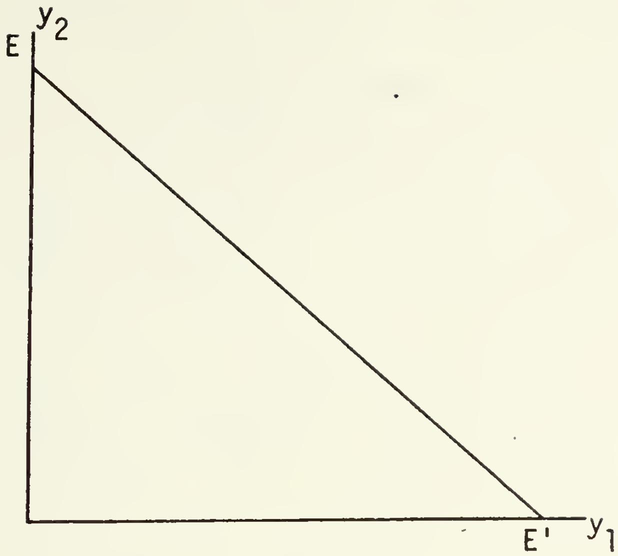


Figure 2.1.

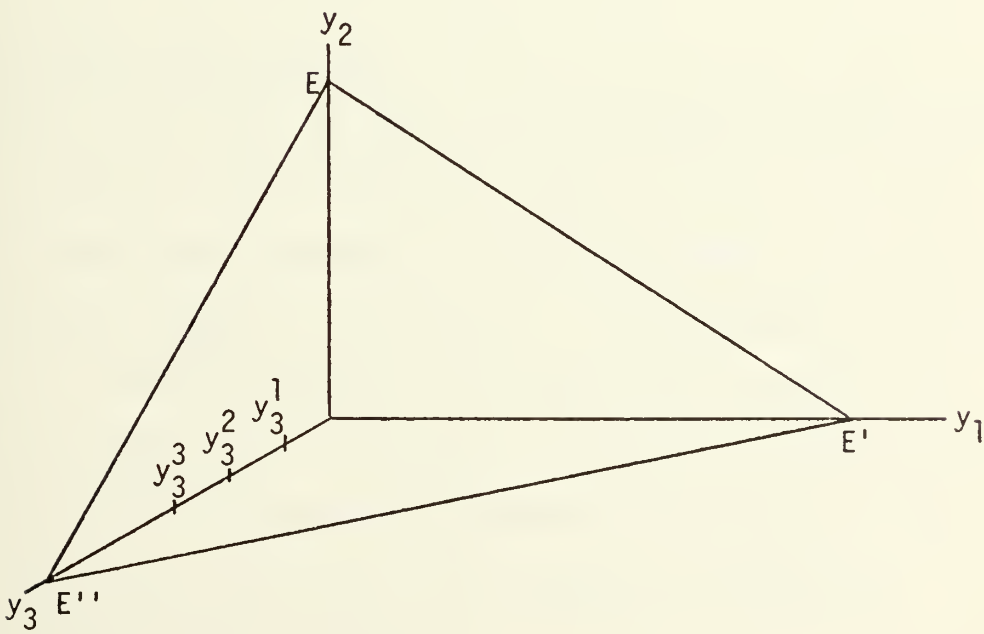


Figure 2.2.

Figure 2.3 is a projection of Figure 2.2 into the $y_1 - y_2$ plane. For each value of y_3, the tradeoffs between y_1 and y_2 are clear.

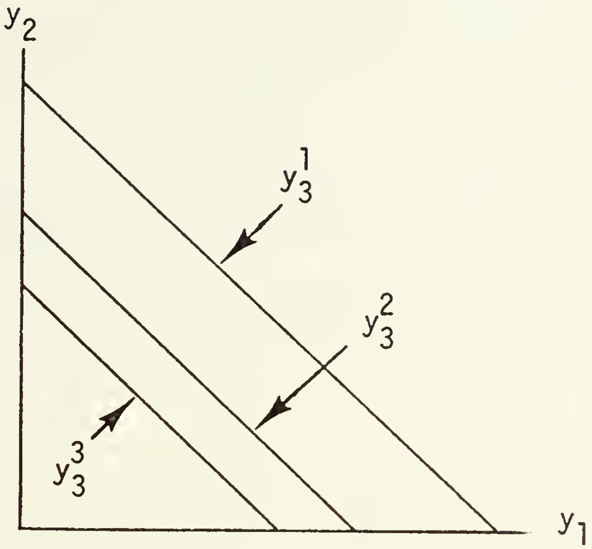


Figure 2.3.

F. A PRACTICAL SOLUTION METHOD

In view of the above, the model will be modified so that the decision maker can examine tradeoffs between any three of the project types.

Fix all but three components of Y at their minimum value, which is the appropriate component of the vector C. Of the remaining three components of Y, two are <u>initially</u> to be fixed at their minimum levels. Arrange the project types so that these components of Y are numbered two and three. The last remaining component of Y is not to be fixed. Arrange the project types so that this component is labeled y_1.

Now consider the linear program:

$$\begin{aligned} \text{maximize} \quad & y_1 \\ \text{subject to:} \quad & A\omega \le B \\ & y_1 \ge c_1 \quad . \end{aligned}$$

ω in this program is a column vector of order n, $(y_1, d_2, d_3, c_4, c_5, \ldots, c_n)$. Initially, $d_2 = c_2$ and $d_3 = c_3$. A solution to this linear program can be found. Now, a sensitivity analysis can be performed on the solution, varying d_2 while d_3 is held constant. After the sensitivity analysis has been performed over the desired range of values of d_2, d_3 can be increased and the sensitivity analysis repeated. The entire process can be repeated over the desired range of values of d_3, each time allowing d_2 to vary over its desired range of values.

In the above linear program, the constraints $A\omega \leq B$ can be written as:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & \cdots & a_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ a_{m1} & a_{m2} & a_{m3} & a_{m4} & a_{m5} & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} y_1 \\ d_2 \\ d_3 \\ c_4 \\ c_5 \\ \cdot \\ \cdot \\ \cdot \\ c_n \end{bmatrix} \leq \begin{bmatrix} b_1 \\ b_2 \\ \cdot \\ \cdot \\ b_m \end{bmatrix}$$

Or,

$$a_{i1}\, y_1 + \sum_{j=2}^{3} a_{ij}\, d_j + \sum_{j=4}^{n} a_{ij}\, c_j \leq b_i, \quad i=1,\ldots,m.$$

For each i such that $a_{i1} \neq 0$, compute:

$$z_i = \frac{1}{a_{i1}} \left[b_i - \sum_{j=2}^{3} a_{ij}\, d_j - \sum_{j=4}^{n} a_{ij}\, c_j \right]$$

Let $\underline{y} = \min_i z_i$.

Each z_i is the number of units of project 1 which could be completed if skill type i were the only skill type required. The minimum of all the

the z_i's is the maximum number of units of project 1 which can be completed. Suppose we let:

$$y^* = \begin{cases} \underline{y}, \text{ if } y_1 \text{ is not required to be an integer.} \\ \text{The largest integer smaller than } \underline{y}, \text{ if } y_1 \text{ is} \\ \text{required to be an integer.} \end{cases}$$

Note that if y_1 is required to be an integer, $\underline{y}$ is truncated, since it would not be possible to construct another complete unit of project 1 with the available resources. This can cause difficulties, since the point $(y_1; d_2, d_3, c_4, \ldots, c_n)$ may be rendered inefficient. This situation is illustrated in Figure 2.4.

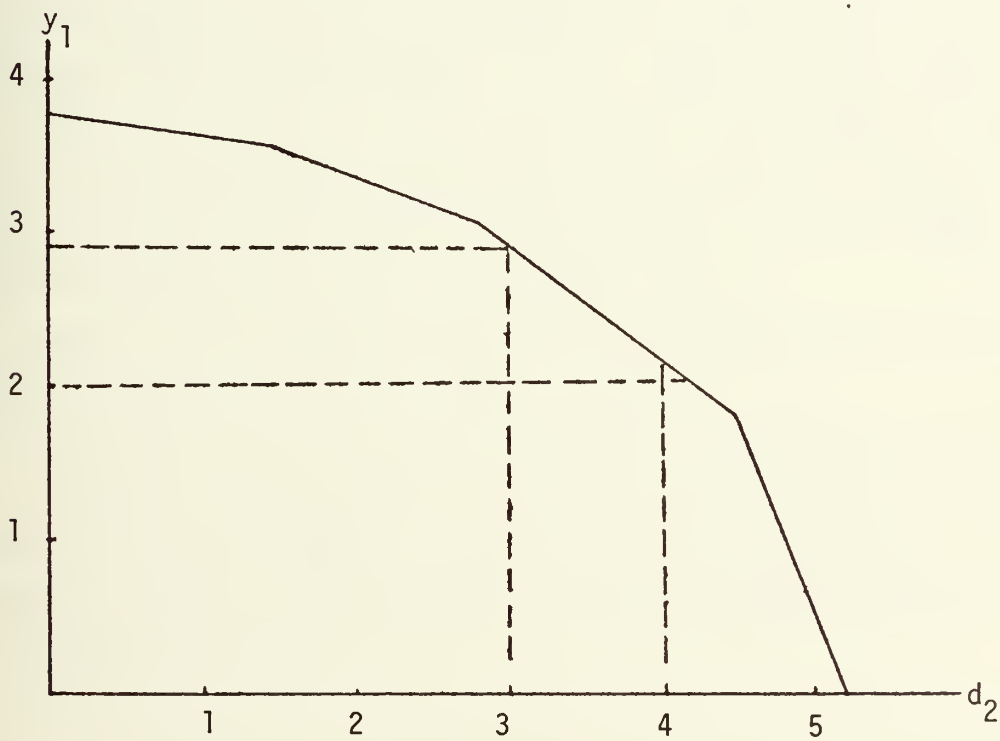


Figure 3.4.

For a particular value of d_3 and for $d_2 = 3$, truncation yields $y_1 = 2$. However, for $y_1 = 2$, d_2 could be increased to 4 (or more, if

d_2 is allowed to take on non-integer values). This problem will not arise if y_1 is not required to be an integer. In what follows, it will be assumed that y_1 is not required to be an integer.

Also, at each iteration it must be ascertained that for all i such that $a_{i1} = 0$,

$$b_i - \sum_{j=2}^{3} a_{ij} d_j - \sum_{j=4}^{n} a_{ij} c_j \geq 0 \quad .$$

If this is not true, then for some skill, there is insufficient labor available to complete the required number of Projects 2 through 12.

If the above is true, and if y_1 is not required to be an integer, and if $y^* = \underline{y} \geq c_1$, then $y_1 = y^*$ is possibly a feasible solution. Let I_j be the amount by which it is desired to increase the number of units of Project Type j at each step, j = 2,3. Then, calculate a new value of y_1, call it y_1', using $d_2 + I_2$ in place of d_2. d_3 remains at its original value. Then, calculate another value of y_1, call it y_1'' using d_2 at its original value and $d_3 = d_3 + I_3$ in place of d_3.

Then, y_1 is a feasible solution, and the point (y_1, d_2, d_3) is an efficient point if, and only if $y_1' < y_1$ and $y_1'' < y_1$.

If d_3 (and $c_4, \ldots, c_n$) are fixed and d_2 is allowed to vary continuously, y_2 and d_2 are related as shown in Figure 3.5. This is somewhat similar to the parametric linear programming problem described in Chapter 5 of Ref. 7.

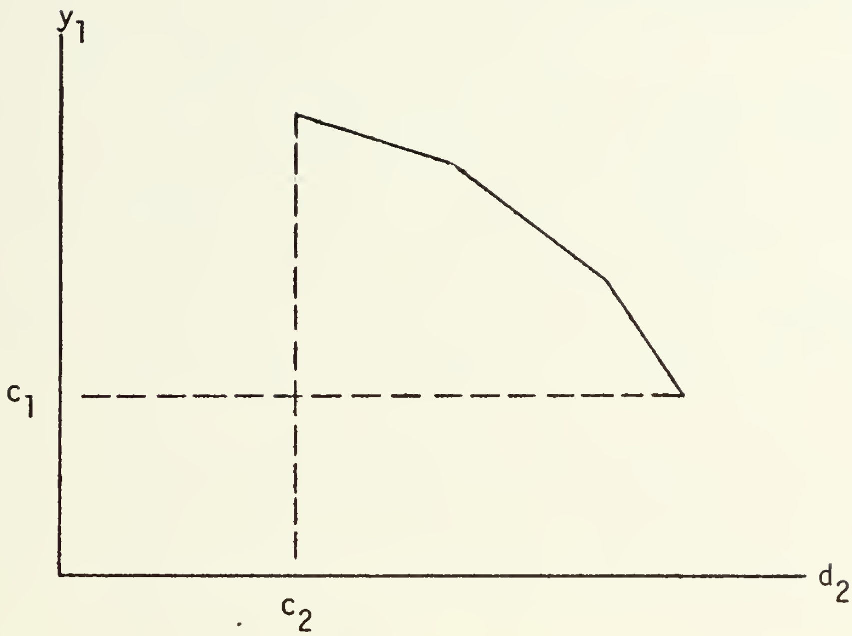


Figure 3.5.

III. THE DATA PROBLEM

The data required for use in this model are the elements of the matrix A and the components of the vector B.

In general, horizontal construction tends to be equipment intensive, while vertical construction tends to be labor intensive. Therefore, the matrix A and the vector B will be partitioned as follows:

a_{ij} = man-hours (equipment-hours) of skill i (equipment type i) required to complete one unit of project type j, $i=1, \ldots r$ $(i = r + 1, \ldots m)$.

b_i = man-hours (equipment-hours) available in the engineer force of skill i (equipment type i), $i = 1, \ldots r$ $(i = r + 1, \ldots m)$.

Equipment operators are not included in the skills $i = 1, \ldots r$. It is assumed that if b_i equipment-hours are available of equipment type i, then sufficient operators are available to operate the equipment.

A. DATA FOR THE TECHNOLOGY MATRIX

The element a_{ij} of the matrix A is the number of man-hours of skill i (or equipment-hours of equipment type i) required to complete one unit of project type j. Reference 3 contains estimates of these numbers for a very large number of project types. Unfortunately, the actual numbers are given in terms of only three skill types, namely "horizontal" construction effort, "vertical" construction effort, and "general labor." The specific skill types which make up the three broad classifications are listed in Ref. 3 and those which are considered applicable to this model are shown in Table I.

TABLE I

SKILL GROUPINGS

Vertical	Airtool operators Carpenters and helpers Cement finishers and helpers Chainsaw operators Electricians and helpers Iron workers Linemen and helpers Masons Millwrights Pipefitters and helpers Pipelayers and helpers Plumbers and helpers Refrigeration mechanics Riggers Sheet metal workers Steel erectors Tinsmiths Welders and helpers
Horizontal	Asphalt plant operators Asphalt surfacing equipment operators Concrete mixer operators Crane operators and oilers Dozer operators Dragline operators Grader operators Powdermen Quarry machine operators Rodmen and chainmen Roller operators Shovel operators Surveyors Tractor operators Truck drivers
General Labor	All types

The actual numbers are not disaggregated below the level of these three broad classifications. The difficulty here is obvious. For example, for a project requiring a certain number of man-hours of vertical construction effort, it is impossible to determine how the requirements for man-hours are distributed among carpenters, plumbers, electricians, etc. The solution to this difficulty is to disaggregate the currently available estimates into estimates which match the specific skills shown in Table I. In fact, it would seem that in order to know how many man-hours of vertical labor are required to complete one unit of a certain structure, the writers of Ref. 3 very well might have known how many man-hours are required of carpentry labor, how many man-hours are required of electrical labor, etc. For horizontal labor, a similar statement can be made.

Disaggregating the a_{ij}'s into the skills shown in Table I does not completely solve the problem, since in the Marine Corps, a person's skill is denoted by his Military Occupational Specialty (MOS). The numbers and titles of the MOS's in Marine Corps Engineer Battalions are given in Refs. 4, 5, and 6. The MOS's of the persons in Marine Corps Engineer Battalions who are considered to contribute direct labor are shown in Table II.

As can be seen, there is not a one-to-one correspondence between the skills listed in Table I and the MOS's listed in Table II. So, for vertical skills, rodman, chainmen, surveyors and, general labor, the a_{ij}'s must be reaggregated so that the skills listed in Table I can be matched with the MOS's listed in Table II. How this might be done is shown in Table III. An entry in the left column of Table III is a skill listed in Table I. The corresponding entry in the center column is the MOS of the

TABLE II

MARINE ENGINEER MOS's

MOS NUMBER	TITLE
1141	Electrician
1161	Refrigeration mechanic
1316	Metal worker
1345	Engineer equipment operator
1371	Combat engineer
1443	Construction surveyor
3531	Motor vehicle operator
1121	Plumbing and water supply man

TABLE III

SKILLS RELATED TO MOS's

SKILLS	MOS	INDEX
Pipefitters and helpers	1121	
Pipelayers and helpers		1
Plumbers and helpers		
Electricians and helpers	1141	
Linemen and helpers		2
Refrigeration mechanics	1161	3
Sheet metal workers	1316	4
Tinsmiths		
Welders and helpers		
Iron workers		
Airtool operators	1371	5
Carpenters and helpers		
Cement finishers and helpers		
Chainsaw operators		
Masons		
Riggers		
Steel erectors		
Powdermen		
General labor		
Rodmen and chainmen	1443	6
Surveyors		

Marine who possesses the skill in the left column. The entry in the right column of Table III corresponds to the index i in the coefficients a_{ij}, $i = 1, \ldots r$.

For the horizontal skills listed in Table I (except rodmen, chainmen, and surveyors), the a_{ij}'s represent hours of a specific type of equipment. These coefficients must not be reaggregated since in general, one hour's work of one type of equipment is not a substitute for one hour's work of another type of equipment.

B. DATA FOR THE RESOURCE AVAILABILITY VECTOR

The vector B is a vector of resource availabilities of the engineer force. As stated previously, these availabilities will be expressed as man-hours in some cases, as equipment-hours in others. First, consider those cases where the resource availabilities are expressed as man-hours. Recall $B = hD$, or $b_i = hd_i$, $i = 1, \ldots, r$, where di is the number of men who possess skill i, expressed as MOS i, and who are available for direct labor. The way in which the d_i's are determined will depend on the situation for which the planning is being done.

If the planning is being done for an operation to commence in the very near future and the identity of all the units in the engineer force is known, the planners should use the actual on-hand strengths of the units to calculate the d_i's. That is, to calculate d_i, the planners will sum, overall the units in the engineer force, the number of men (available for direct labor) in each unit who hold MOS i. To summarize, let δ_{ik} be the on-hand strength of unit k of persons with MOS i. Then:

$$d_i = \sum_k \delta_{ik}, \quad i = 1, \ldots, r.$$

If the plan is for an operation so far in the future that it is impossible to make reasonable estimates of on-hand strengths or if the plan is for a hypothetical situation, the planners should make estimates based on unit Tables of Organization (T/O's).

A unit T/O contains the number of military personnel authorized that unit in each grade and in each MOS. Also, the T/O contains the unit organization. That is, the T/O shows how battalions are organized into companies, companies into platoons, etc. The T/O contains the title of every billet in the unit, and the grade and MOS of the person who would ideally be assigned to that billet.

Thus, the planners must examine the T/O of each unit in the engineer force and decide which billets contribute direct labor. This will largely be a matter of the planner's judgement and experience. Then, the planners must, for each MOS, sum over all units in the engineer force the billets that contribute direct labor. After making the calculations described above, the planners must adjust the numbers obtained to account for the fact that units rarely have on hand exactly the number of persons authorized by the T/O. To summarize, let δ_{ik} be the number of billets authorized by T/O in the direct labor force of unit k with MOS i. Then,

$$d_i = \sum_k \alpha_{ik} \delta_{ik}, \; i = 1, \ldots, r.$$

For skill i and unit k, α_{ik} is the fraction of T/O strength which is used to make allowances for planned for overages or shortages in T/O strength. The α_{ik}'s may be based on historical data, may be given by higher authority or may be used as parameters by the planners.

For those b_i's which are expressed as equipment-hours (i = r +1, ..., m), the procedure is much the same. For an operation to be

conducted in the very near future:

$$d_i = \sum_k \delta_{ik}, \; i = r + 1, \ldots, m,$$

where δ_{ik} is the number of pieces of equipment type i that unit k has on hand. For an operation far in the future or a hypothetical operation,

$$d_i = \sum_k \alpha_{ik} \, \delta_{ik}, \; i = r + 1, \ldots, m,$$

where now δ_{ik} is the number of pieces of equipment type i unit k is authorized in its Table of Equipment (T/E). Again, the α_{ik}'s may be based on historical data, may be given by higher authority, or may be used as parameters by the planners.

C. DATA COMPATIBILITY

Finally, it must be ensured that all factors which affect production have been accounted for, but that none has been counted twice. For example, the b_i's depend on the number of working hours per day, which could depend (among other things) on the effects of climate. Ref. 3 gives a_{ij}'s for temperate climates and adjustment factors for other than temperate climates. If, in using the model, the a_{ij}'s are all multiplied by an adjustment factor to account for the effects of a non-temperate climate, then the b_i's <u>would</u> <u>not</u> be divided by the adjustment factor. However, the b_i's might also be affected because troops generally work fewer hours per day in non-temperate climates and the adjustments in the a_{ij}'s would not reflect this fact.

In summary, the units of a_{ij} are:

$$\frac{\text{productive man-hours of skill i}}{\text{unit of project type j}} \quad .$$

The units of b_i are:

$$\text{total man-hours of skill } i \cdot \frac{\text{productive man-hours of skill } i}{\text{total man-hours of skill } i} =$$

productive man hours of skill i.

IV. TEST PROBLEM

A. PURPOSE

The purpose of the test problem is to test the algorithm and to verify the validity of a computer program written to exercise the algorithm. The test problem takes as given the data in the appropriate form. The project types and skill types are completely hypothetical. The direct inputs to the computer program used in the test problem are A, B, and C. It is assumed that all necessary adjustments to the a_{ij}'s and b_i's have been made. The test problem used ten skill types and twelve project types.

The computer program was written in FORTRAN and run on the Naval Postgraduate School computer. A flow chart is shown on pages

B. DATA

Three runs of the test problem were made using different sets of data. The two sets of data are shown in Tables IV, V, and VI. In each run, the value of d_2 was increased by five at each iteration and the value of d_3 by 1.

C. RESULTS

The results of the three runs of the test problem are shown on pages 42-50. In Run 1, a_{i1} was either of the same magnitude as a_{i2} and a_{i3}. (meaning perhaps twice as large) or much larger (perhaps one thousand times larger). The algorithm did find the efficient points, however, the value of y_1 changed very little as the values of d_2 and d_3 were increased. This happened because, for most skills, an increase in the number of units of Project Types 2 and 3 did not reduce the amount of

TABLE IV

DATA FOR RUN 1

a_{ij}

i \ j	1	2	3	4	5	6
1	0.0	0.0	30.00	150.00	90.00	0.0
2	0.0	12.00	20.00	250.00	20.00	23.00
3	0.0	1.0	2.00	14.00	3.00	4.00
4	1600.00	1.00	1.00	12.00	2.50	4.50
5	500.00	0.50	0.50	7.50	2.00	2.00
6	1200.00	0.40	0.40	5.00	1.50	0.75
7	0.0	2.00	2.00	20.00	5.00	7.00
8	100.00	120.00	300.00	1600.00	600.00	500.00
9	250.00	1.00	1.00	6.00	2.00	3.00
10	2000.00	1.00	2.00	15.00	4.00	5.00

a_{ij}

i \ j	7	8	9	10	11	12
1	0.0	100.00	0.0	0.0	0.0	0.0
2	18.00	25.00	15.00	0.0	20.00	2.00
3	2.50	4.00	0.0	0.0	2.00	0.0
4	3.00	3.00	3.00	160.00	1.50	0.25
5	1.00	2.00	2.50	160.00	1.00	0.10
6	1.50	0.50	2.00	20.00	0.50	0.10
7	4.00	6.00	4.00	0.0	3.00	0.75
8	500.00	550.00	600.00	0.0	200.00	40.00
9	2.00	2.00	2.00	2.00	1.00	0.50
10	3.00	5.00	12.00	50.00	2.00	1.00

j	1	2	3	4	5	6	7	8	9	10	11	12
c_j	5	125	3	1	2	1	3	2	1	3	1	20

i	1	2	3	4	5
b_i	900.0	2700.0	250.0	1700.0	6000.0

i	6	7	8	9	10
b_i	13000.0	500.0	32000.0	2800.0	21000.0

TABLE V

DATA FOR RUN 2

a_{ij}

i \ j	1	2	3	4	5	6
1	20.00	0.0	30.00	150.00	90.00	0.0
2	0.0	12.00	20.00	250.00	20.00	23.00
3	0.0	1.00	5.00	14.00	3.00	4.00
4	1600.00	750.00	200.00	12.00	2.50	4.50
5	200.00	100.00	1500.00	7.50	2.00	2.00
6	1200.00	900.00	1050.00	5.00	1.50	0.75
7	3.00	10.00	0.0	20.00	5.00	7.00
8	100.00	120.00	60.00	1600.00	600.00	500.00
9	250.00	190.00	350.00	6.00	2.00	3.00
10	2000.00	1750.00	1900.00	15.00	4.00	5.00

a_{ij}

i \ j	7	8	9	10	11	12
1	0.0	100.00	0.0	0.0	0.0	0.0
2	18.00	25.00	15.00	0.0	20.00	2.00
3	2.50	4.00	0.0	0.0	2.00	0.0
4	3.00	3.00	3.00	160.00	1.50	0.25
5	1.00	2.00	2.50	160.00	1.00	0.10
6	1.50	0.50	2.00	20.00	0.50	0.10
7	4.00	6.00	4.00	0.0	3.00	0.75
8	500.00	550.00	600.00	0.0	200.00	40.00
9	2.00	2.00	2.00	2.00	1.00	0.50
10	3.00	5.00	12.00	50.00	2.00	1.00

j	1	2	3	4	5	6	7	8	9	10	11	12
c_j	5	30	3	1	2	1	3	2	1	3	1	20

i	1	2	3	4	5
b_i	1000.0	1400.0	150.0	64000.0	21000.0

i	6	7	8	9	10
b_i	75000.0	800.00	17000.0	17000.0	150000.0

TABLE VI

DATA FOR RUN 3

a_{ij}

i \ j	1	2	3	4	5	6
1	20.00	0.0	30.00	150.00	90.00	0.0
2	0.0	12.00	20.00	250.00	20.00	23.00
3	0.0	1.00	5.00	14.00	3.00	4.00
4	1600.00	750.00	200.00	12.00	2.50	4.50
5	200.00	100.00	1500.00	7.50	2.00	2.00
6	1200.00	900.00	1050.00	5.00	1.50	0.75
7	3.00	10.00	0.0	20.00	5.00	7.00
8	100.00	120.00	60.00	1600.00	600.00	500.00
9	250.00	190.00	350.00	6.00	2.00	3.00
10	2000.00	1750.00	1900.00	15.00	4.00	5.00

a_{ij}

i \ j	7	8	9	10	11	12
1	0.0	100.00	0.0	0.0	0.0	0.0
2	18.00	25.00	15.00	0.0	20.00	2.00
3	2.50	4.00	0.0	0.0	2.00	0.0
4	3.00	3.00	3.00	160.00	1.50	0.25
5	1.00	2.00	2.50	160.00	1.00	0.10
6	1.50	0.50	2.00	20.00	0.50	0.10
7	4.00	6.00	4.00	0.0	3.00	0.75
8	500.00	550.00	600.00	0.0	200.00	40.00
9	2.00	2.00	2.00	2.00	1.00	0.50
10	3.00	5.00	12.00	50.00	2.00	1.00

j	1	2	3	4	5	6	7	8	9	10	11	12
c_j	5	30	0	1	2	1	3	2	1	3	1	20

i	1	2	3	4	5
b_i	800.0	1300.00	120.0	62000.0	12000.0

i	6	7	8	9	10
b_i	70000.0	800.0	16000.0	15000.0	130000.0

labor available for Project Type 1. This case represents a situation in which tradeoffs are examined between Project Type 1 which, for the most part, requires either (but not both) horizontal or vertical skills, and Project Types 2 and 3 which, for the most part, require the opposite type skills.

In Run 2, a_{i1}, a_{i2}, and a_{i3} were all nearly the same magnitude. This case represents a situation in which tradeoffs are examined between three projects all of which require the various skills in about the same proportion. The algorithm did find the efficient points and in this case y_1 changed considerably as d_2 and d_3 were increased.

Run 3 illustrates the efficient tradeoffs when one unit of a large project is introduced. In this case, d_3 was allowed to only take on values of zero and one.

V. CONCLUSIONS

A. MODEL LIMITATIONS

Between projects which require essentially the same skills (as in Run 2) the model appears to be useful for generating meaningful information from which a decision maker could analyze tradeoffs. The model appears to be of limited usefulness, however, in generating information about tradeoffs between projects which require essentially different skills (as in Run 1).

The most serious limitation on the value of the model is the nonavailability of data for the technology matrix in the appropriate form. The development of the required data, while simple, could be costly. Further, if the data were developed, it would have to be for some sort of "average" conditions, which would seldom, if ever, be encountered in the field. Thus, anyone using the model for planning purposes should not expect to necessarily achieve in the field an efficient point calculated using the model.

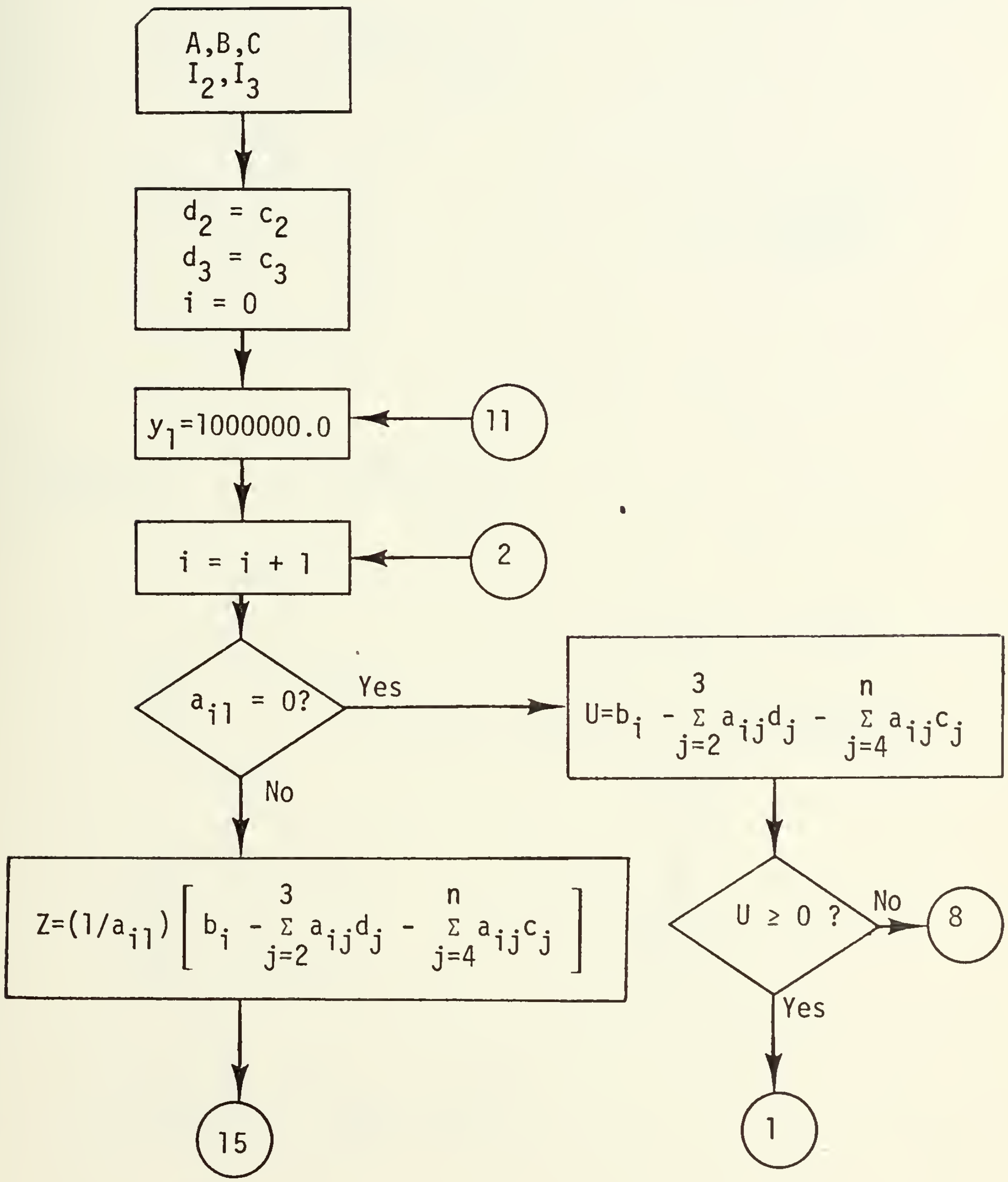
B. ANOTHER APPLICATION OF THE MODEL

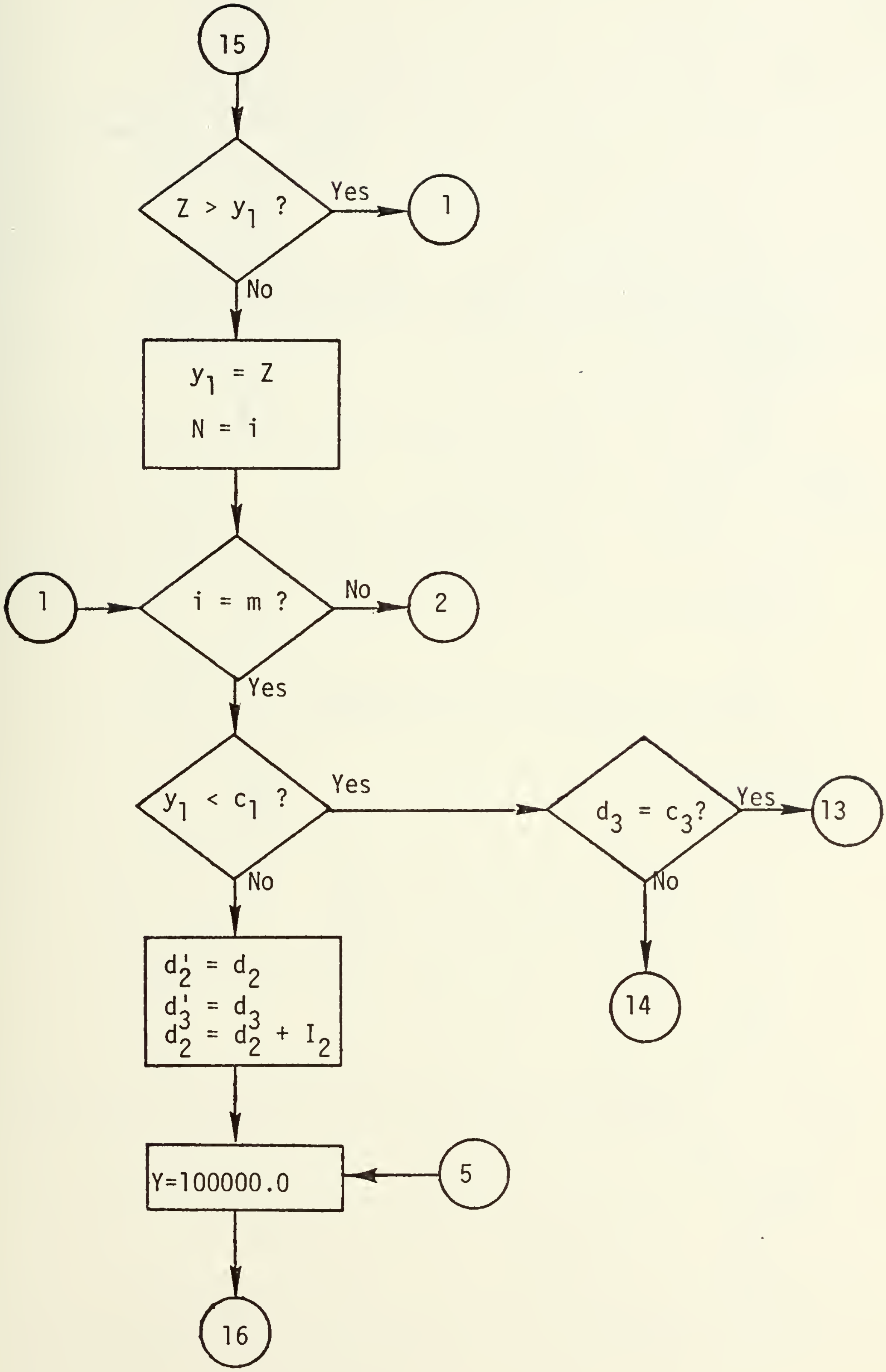
A useful extension of the model would be to perform, at each value of d_2 and d_3, a sensitivity analysis on one or more of the components of the vector B. Such a sensitivity analysis would be useful in the analysis of engineer unit T/O's and T/E's and in engineer force structure and contingency planning. For example, by changing one component of B, the effects of the addition or deletion from the T/O of a given number of Marines of a certain MOS could be evaluated. Changing a single component of B could also represent the addition or deletion of a given

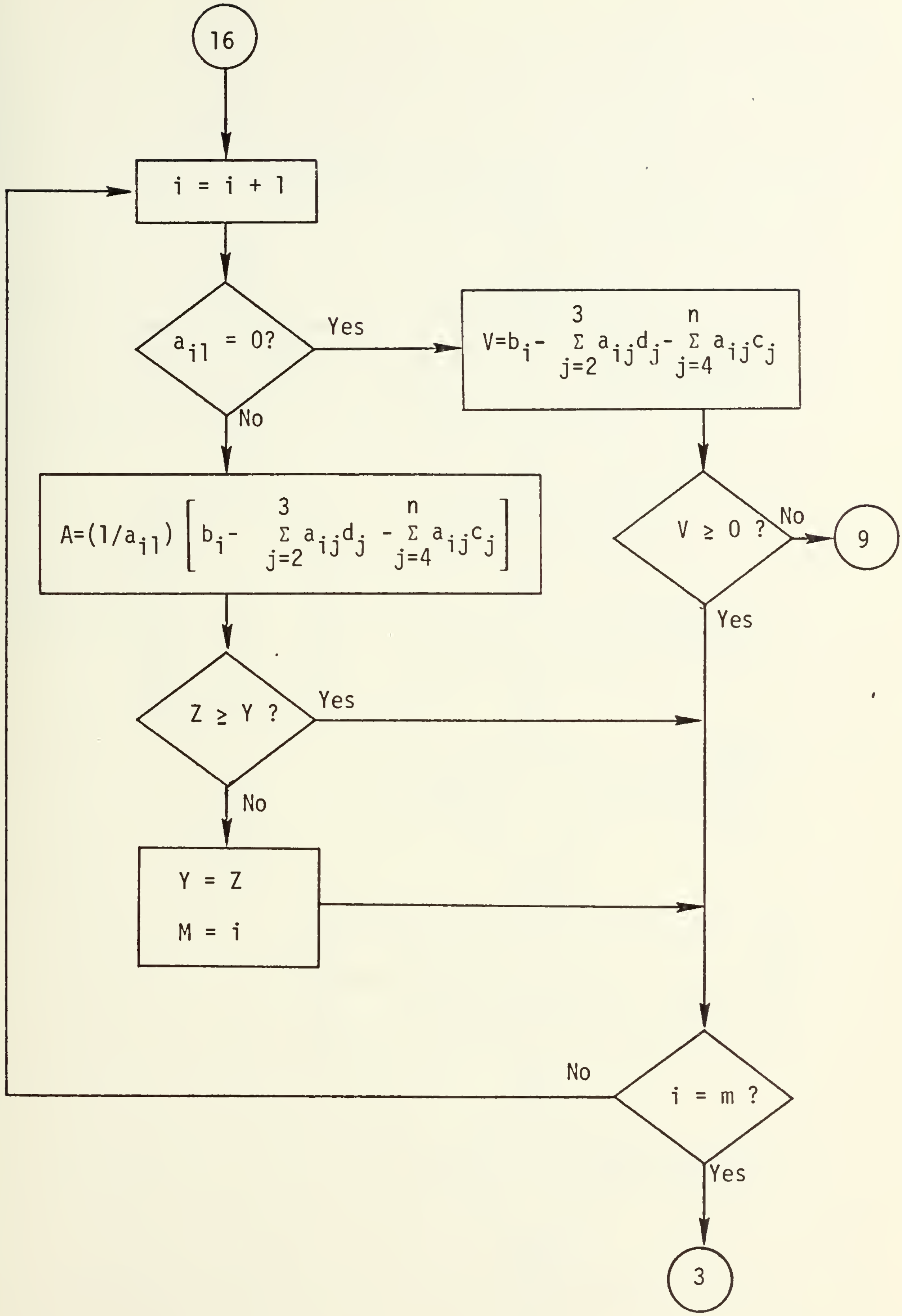
number of pieces of a certain type of equipment from the T/E. Changing several of the components of B could represent the addition or deletion of entire units from the engineer force. Or, changing all the components of B could represent changing the number of days allowed to complete a set of projects or the number of working hours per day. The effects of other changes of interest to the planners can be studied.

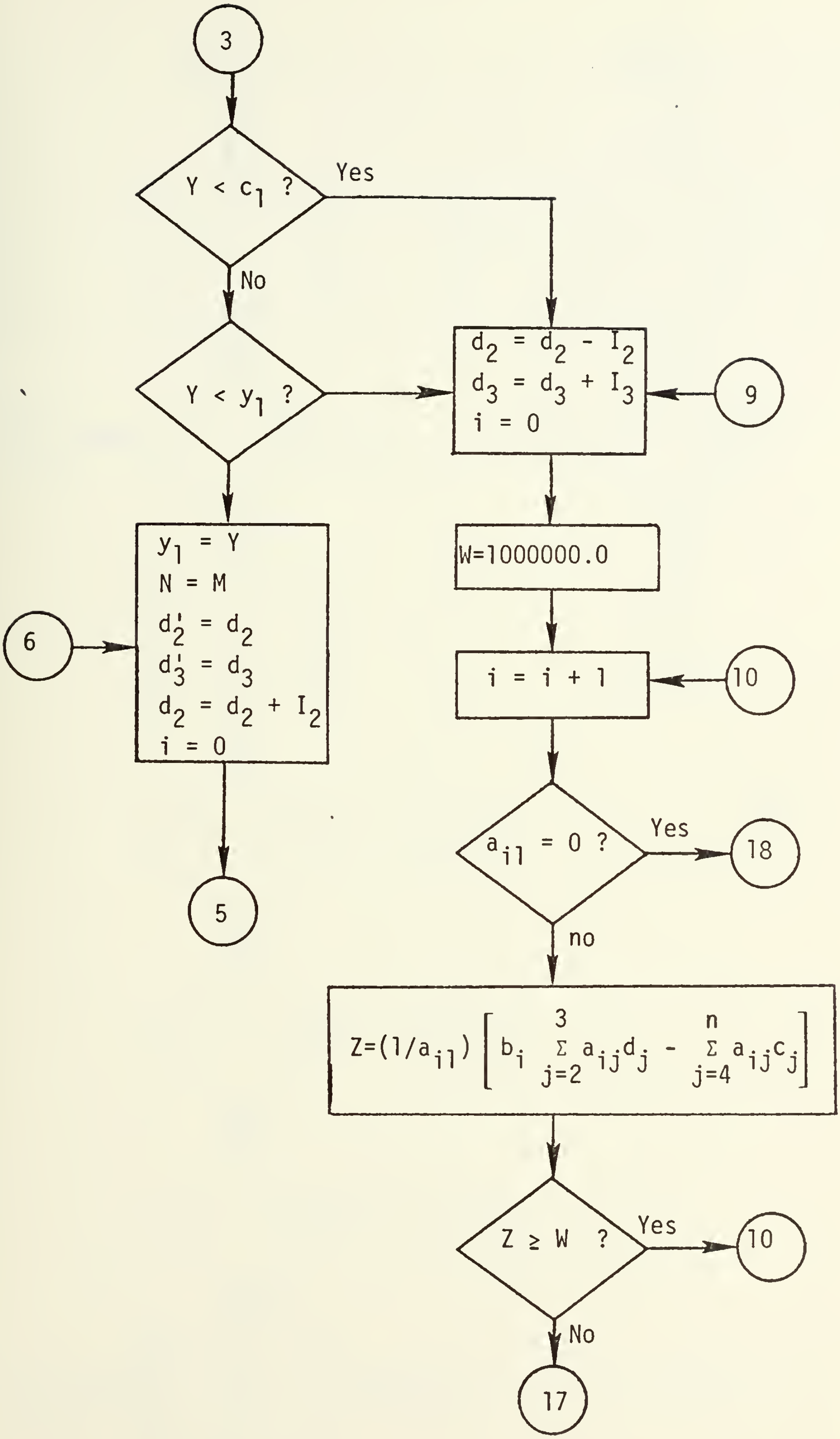
APPENDIX A

FLOW CHART FOR TEST PROBLEM SOLUTION

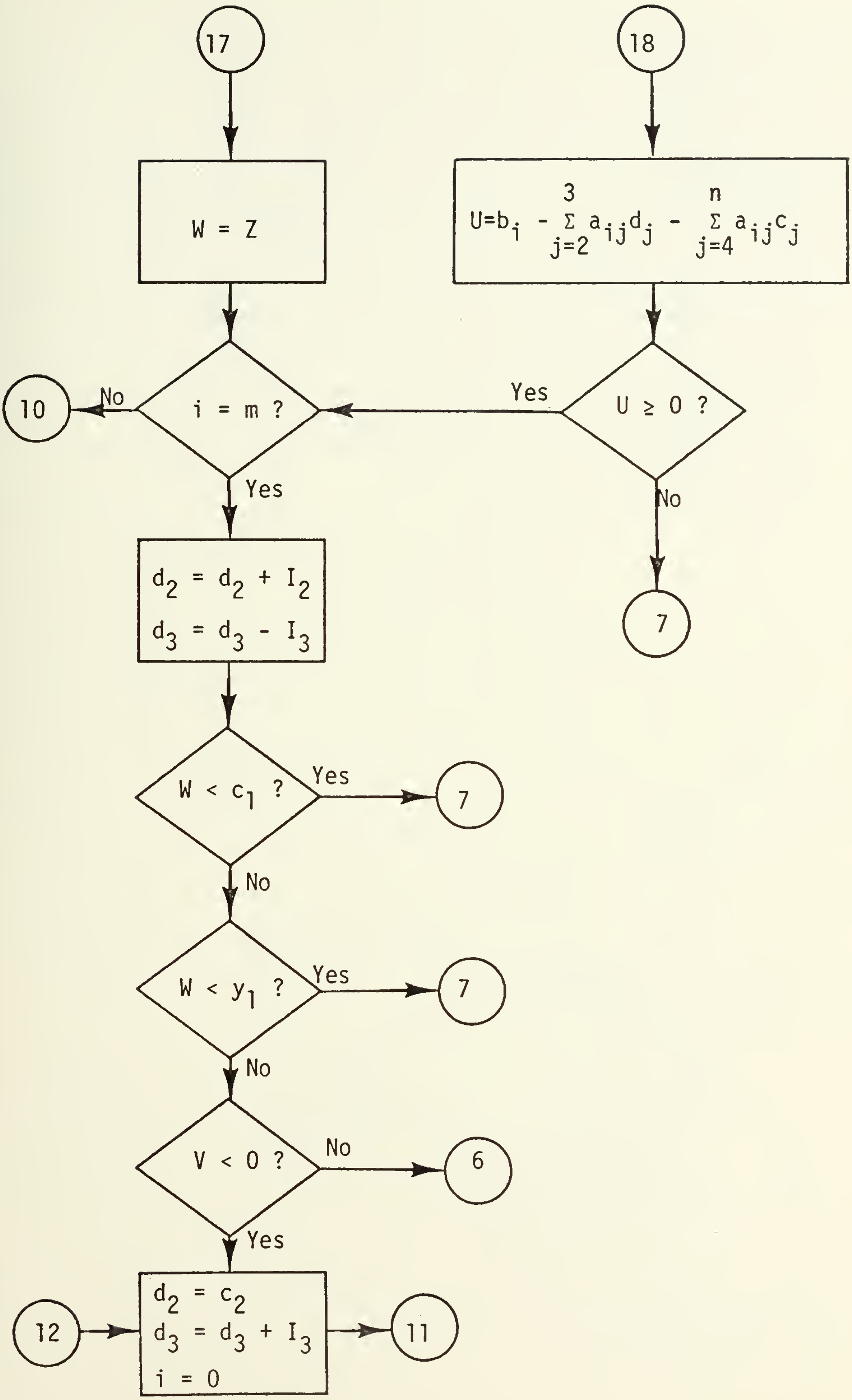



15
Z > y1 ?
Yes
1
No
y1 = Z
N = i
1
i = m ?
No
2
Yes
y1 < c1 ?
Yes
d3 = c3?
Yes
13
No
14
No
d'2 = d2
d'3 = d3
d2 = d2 + I2
Y=100000.0
5
16

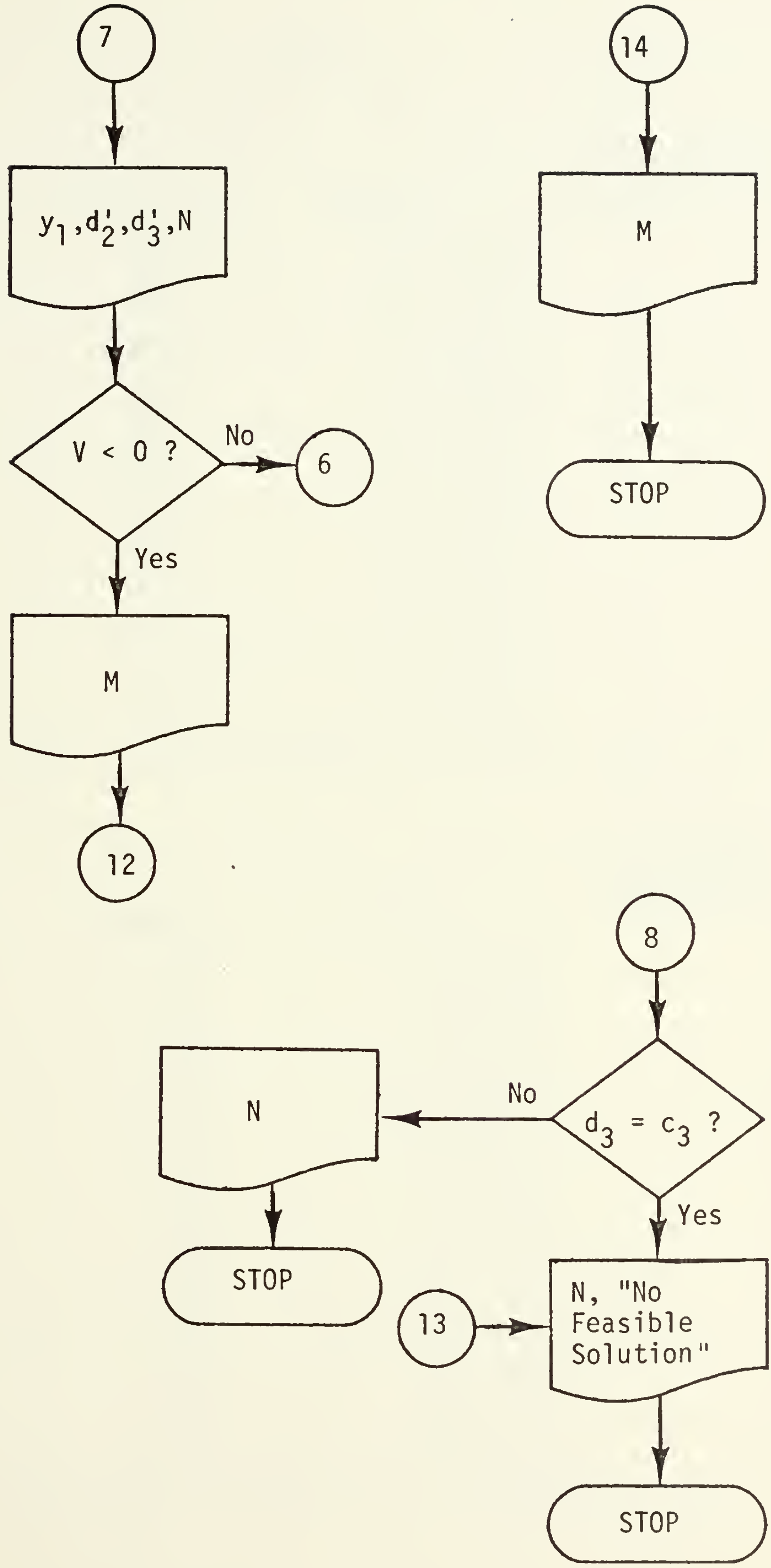

16
i = i + 1
$a_{i1} = 0?$
Yes
$V = b_i - \sum_{j=2}^{3} a_{ij} d_j - \sum_{j=4}^{n} a_{ij} c_j$
No
$A = (1/a_{i1}) \left[b_i - \sum_{j=2}^{3} a_{ij} d_j - \sum_{j=4}^{n} a_{ij} c_j \right]$
$V \geq 0$?
No
9
Yes
$Z \geq Y$?
Yes
No
Y = Z
M = i
No
i = m ?
Yes
3



3
Y < c1 ?
Yes
No
Y < y1 ?
d2 = d2 - I2
d3 = d3 + I3
i = 0
9
y1 = Y
N = M
d'2 = d2
d'3 = d3
d2 = d2 + I2
i = 0
6
5
W=1000000.0
i = i + 1
10
ai1 = 0 ?
Yes
18
no
Z=(1/ai1) [bi Σ j=2 3 aij dj - Σ j=4 n aij cj]
Z ≥ W ?
Yes
10
No
17



17
18
W = Z
$U = b_i - \sum_{j=2}^{3} a_{ij} d_j - \sum_{j=4}^{n} a_{ij} c_j$
10
No
i = m ?
Yes
U ≥ 0 ?
Yes
No
7
$d_2 = d_2 + I_2$
$d_3 = d_3 - I_3$
$W < c_1$?
Yes
7
No
$W < y_1$?
Yes
7
No
V < 0 ?
No
6
Yes
12
$d_2 = c_2$
$d_3 = d_3 + I_3$
i = 0
11


7
y_1, d_2', d_3', N
$V < 0$?
No
6
Yes
M
12
14
M
STOP
8
$d_3 = c_3$?
No
N
STOP
Yes
13
N, "No Feasible Solution"
STOP

COMPUTER OUTPUT

RUN 1

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
3	125	10.21625	4
	130	10.21312	4
	135	10.21000	4
	140	10.20687	4
	145	10.20375	4
	150	10.20062	4
	155	10.19750	4
	160	10.19437	4
	165	10.19125	4
	170	10.18812	4
	175	10.18500	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
4	125	10.21562	4
	130	10.21250	4
	135	10.20937	4
	140	10.20625	4
	145	10.20313	4
	150	10.20000	4
	155	10.19687	4
	160	10.19375	4
	165	10.19062	4
	170	10.18750	4
	175	10.18437	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
5	125	10.21500	4
	130	10.21187	4
	135	10.20875	4
	140	10.20562	4
	145	10.20250	4
	150	10.19937	4
	155	10.19625	4
	160	10.19312	4
	165	10.19000	4
	170	10.18687	4
	175	10.18375	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
6	125	10.21437	4
	130	10.21125	4
	135	10.20812	4
	140	10.20500	4
	145	10.20187	4
	150	10.19875	4
	155	10.19562	4
	160	10.19250	4
	165	10.18937	4
	170	10.18625	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
7	125	10.21375	4
	130	10.21062	4
	135	10.20750	4
	140	10.20437	4
	145	10.20125	4
	150	10.19812	4
	155	10.19500	4
	160	10.19187	4
	165	10.18875	4
	170	10.18562	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
8	125	10.21312	4
	130	10.21000	4
	135	10.20687	4
	140	10.20375	4
	145	10.20062	4
	150	10.19750	4
	155	10.19437	4
	160	10.19125	4
	165	10.18812	4
	170	10.18500	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
9	125	10.21250	4
	130	10.20937	4
	135	10.20625	4
	140	10.20313	4
	145	10.20000	4
	150	10.19687	4
	155	10.19375	4
	160	10.19062	4
	165	10.18750	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
10	125	10.21187	4
	130	10.20875	4
	135	10.20562	4
	140	10.20250	4
	145	10.19937	4
	150	10.19625	4
	155	10.19312	4
	160	10.19000	4
	165	10.18687	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
11	125	10.21125	4
	130	10.20812	4
	135	10.20500	4
	140	10.20187	4
	145	10.19875	4
	150	10.19562	4
	155	10.19250	4
	160	10.18937	4
	165	10.18625	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
12	125	10.21062	4
	130	10.20750	4
	135	10.20437	4
	140	10.20125	4
	145	10.19812	4
	150	10.19500	4
	155	10.19187	4
	160	10.18875	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

LIMITING SKILL FOR AN INCREASE IN PROJECT 3 IS: 1

RUN 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
3	40	19.00000	1
	45	18.20250	4
	50	15.85875	4
	55	13.51500	4
	60	11.17125	4
	65	8.82750	4
	70	5.66667	7

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
4	45	17.50000	1
	50	15.73375	4
	55	13.39000	4
	60	11.04625	4
	65	8.70250	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
5	45	16.00000	1
	50	15.60875	4
	55	13.26500	4
	60	10.92125	4
	65	8.57750	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
6	50	14.50000	1
	55	13.14000	4
	60	10.79625	4
	65	8.43437	6

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
7	55	13.00000	1
	60	10.67125	4

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
8	55	11.50000	1
	60	10.43437	6

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
9	45	10.00000	1
	50	9.97000	5
	55	7.47000	5

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 5

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
10	35	8.50000	1
	40	7.47000	5

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 5

LIMITING SKILL FOR AN INCREASE IN PROJECT 3 IS: 5

RUN 3

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
0	50	13.50000	1
	55	12.64000	4
	60	10.29625	4
	65	7.00000	8

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

PROJECT 3	PROJECT 2	PROJECT 1	LIMITING SKILL FOR AN INCREASE IN PROJECT 1 IS:
1	55	12.00000	1
	60	10.17125	4
	65	6.40000	8

LIMITING SKILL FOR AN INCREASE IN PROJECT 2 IS: 2

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13. ABSTRACT

Given an engineer force structure and a set of projects to be completed in a specified time period by the units of the force structure, the problem which is examined is that of efficient utilization of the excess labor in some skills which is likely to be available after completion of the minimum number of projects. A model is developed in terms of a vector maximization problem. This is reduced to a linear programming problem, which is further reduced to a problem which can be solved by algebraic means. A test problem is run and results presented. A suggestion for an additional use of the model is included.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Marine Corps Engineer Planning						
Engineer planning						

21 APR 75 23752
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